EFFECTS of CONVECTIVE BLOB TRANSPORT on <u>REACTORS</u>

Reference:
"Hollywood"

- **Subject of submitted FED paper: summary here**
- **M. Kotschenreuther (IFS) in collaboration with Tom Rognlien (LLNL), Prashant Valanju (IFS)**
- **New: possible ITER implications discussed here**

Our Physics Understanding of SOL Transport has Changed

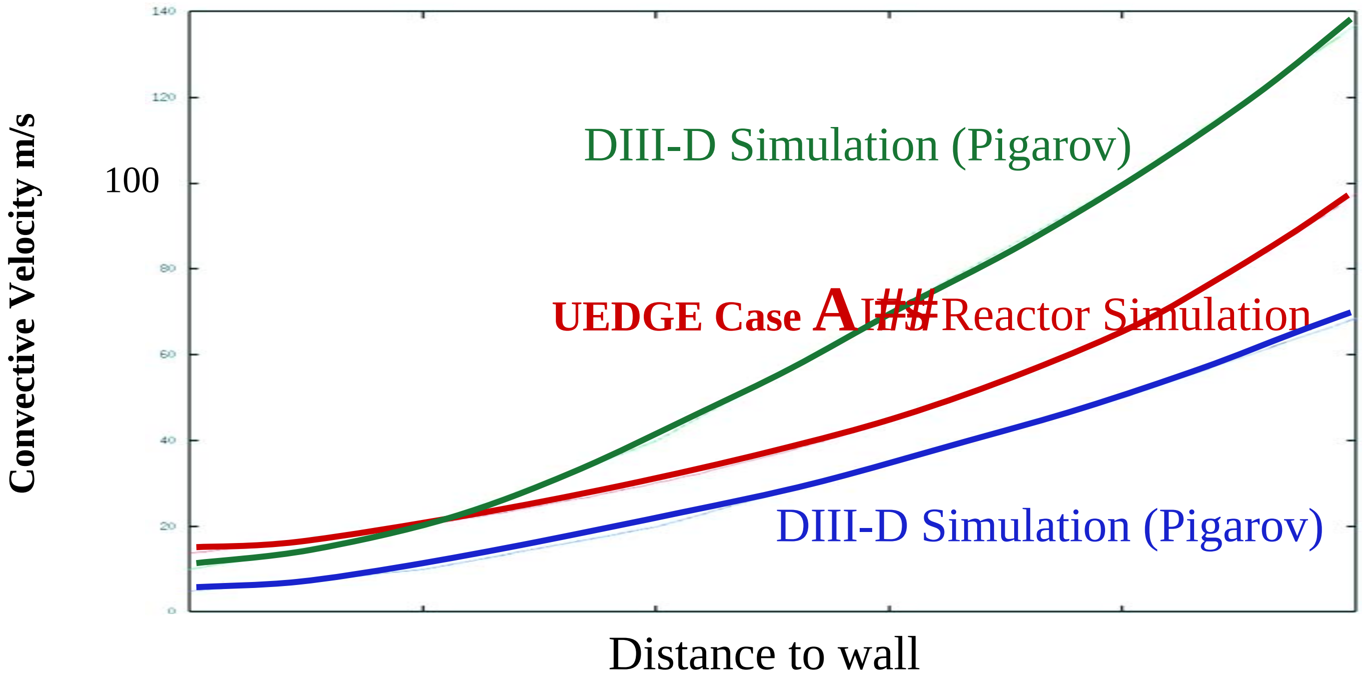
- Pioneering experiments at C-Mod, DIII-D, NSTX: large radial convective transport of plasma blobs
- Theoretical investigations: blobs of plasma should rapidly convect to the main chamber wall
- IFS-LLNL collaboration: investigation of potential *REACTOR* effects of convection *for the first time*

Serious Effects of Blob Convective Transport

- First Wall Erosion
  - A concern mentioned in the literature, but heretofore not estimated for ***reactors***
  - **Serious implications found here**
- Helium Pumping
  - Not discussed in literature, but: ***far SOL transport disproportionately effects helium removal (negatively?)*****--work in progress**

2-D Simulations using UEDGE

- Previous state of the art: use constant empirical ***diffusion*** coefficient for reactor simulation
- But large convection appears essential in far SOL
- To estimate reactor effects: ***use empirically motivated convection model***
  - ***similar to that used to simulate present experiments***



Several Convection Profiles Tried for Reactor to Obtain Best SOL Profile Fit

- **Desire: simulated reactor SOL density profile to match *SOL profile characteristics found in present experiments***
- **Quantitative profile characteristics checked with experiments:**
  1. **Ratio of density in the SOL (d/a=0.04) to separatrix density**
  2. **a/Density scale length at d/a = 0.04**
  3. **Convective flux at d/a = 0.04**

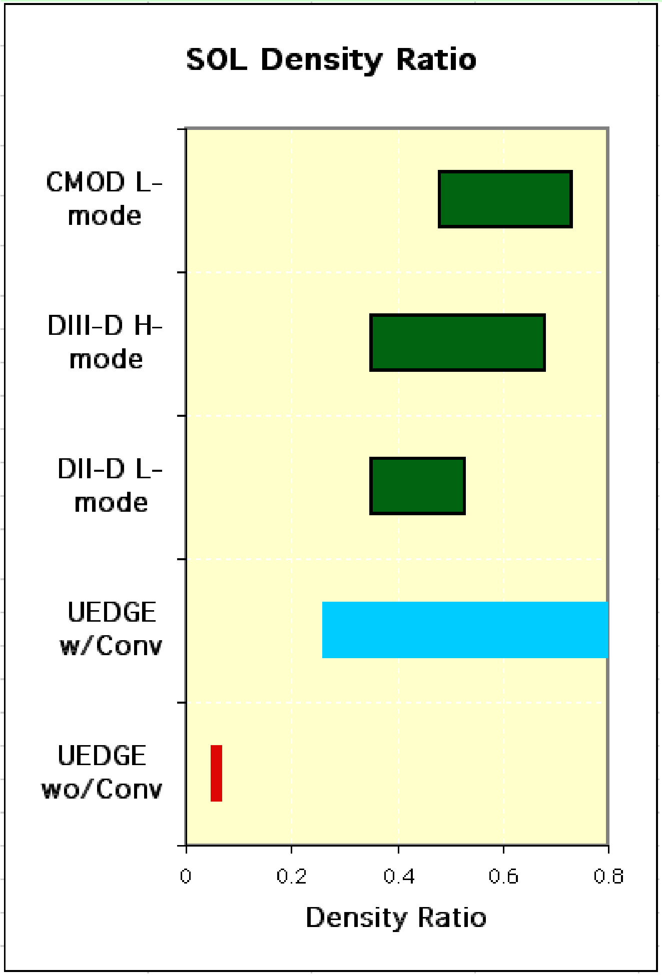
a = minor radius

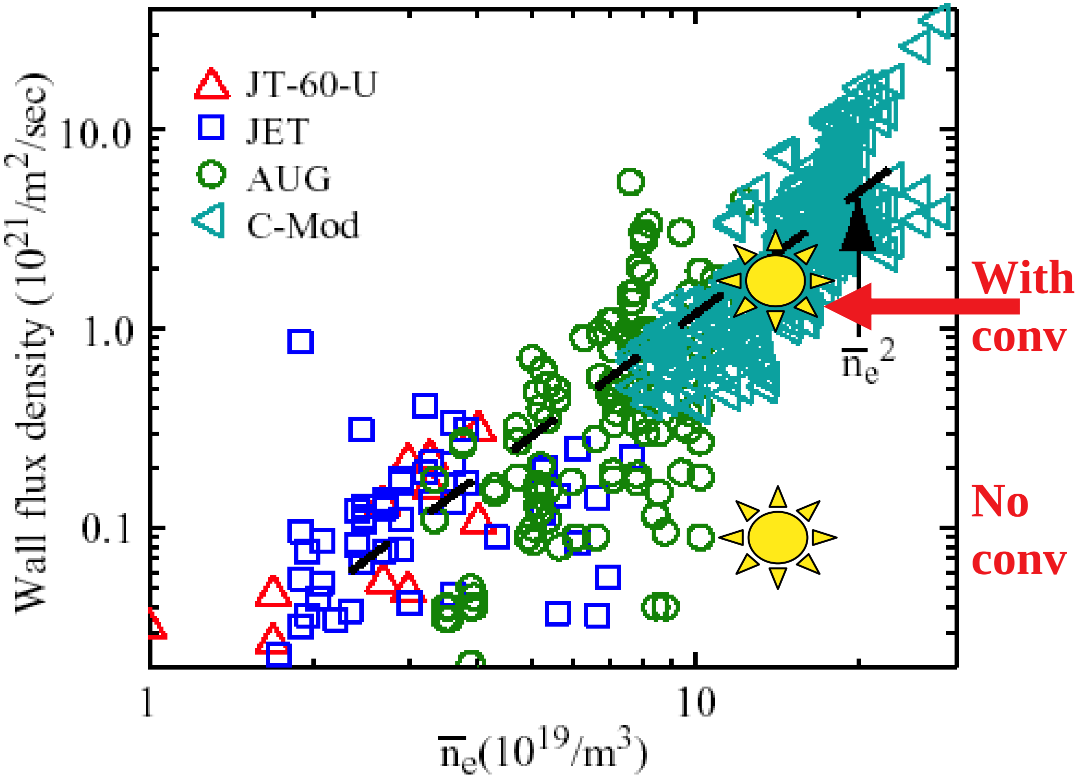
d/a = 0.04 ~ first wall ARIES

- **Four convection profiles tried:**
  - **A) 10 m/s to 100 m/s (found to give *BEST FIT* to data)**
  - **B) 10 m/s to 50 m/s (reduce convection near wall)**
  - **C) 5 m/s to 100 m/s (reduce convection near plasma)**
  - **D) 0 m/s to 0 m/s (no convection)**
- **Find: Case A gives best profile match: reducing the convection (B and C) results in a poorer match to characteristics 1,2 and 3**
- **Case A is also best fit of convection used to model present expts.**

Why Wall Erosion Estimates Based on Models w/o Convection are Likely to be Low

- Standard SOL transport model: constant diffusion ***only***
- Probably underestimates plasma-chamber interaction by ~ 30

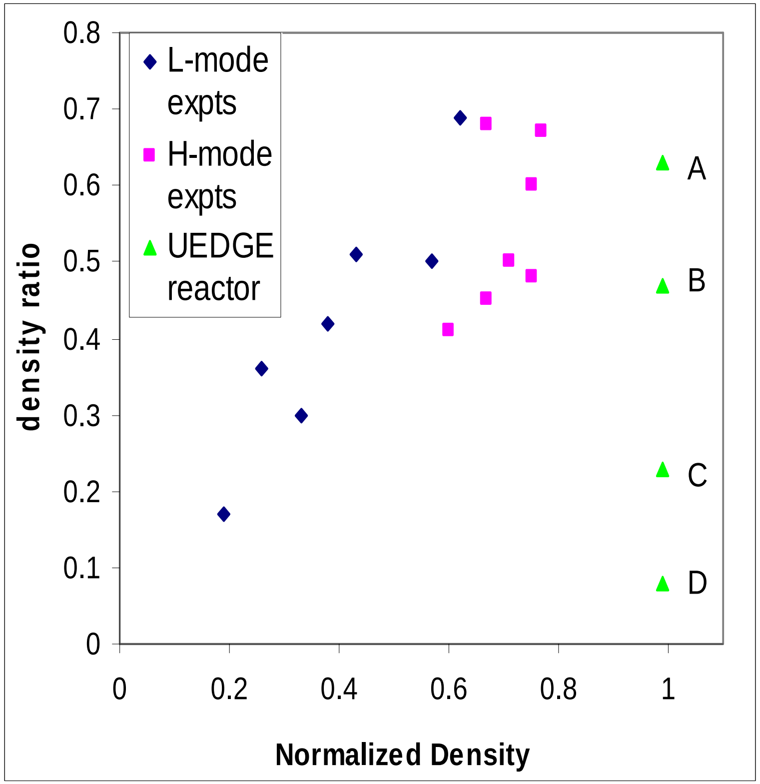




Density Ratio Comparison

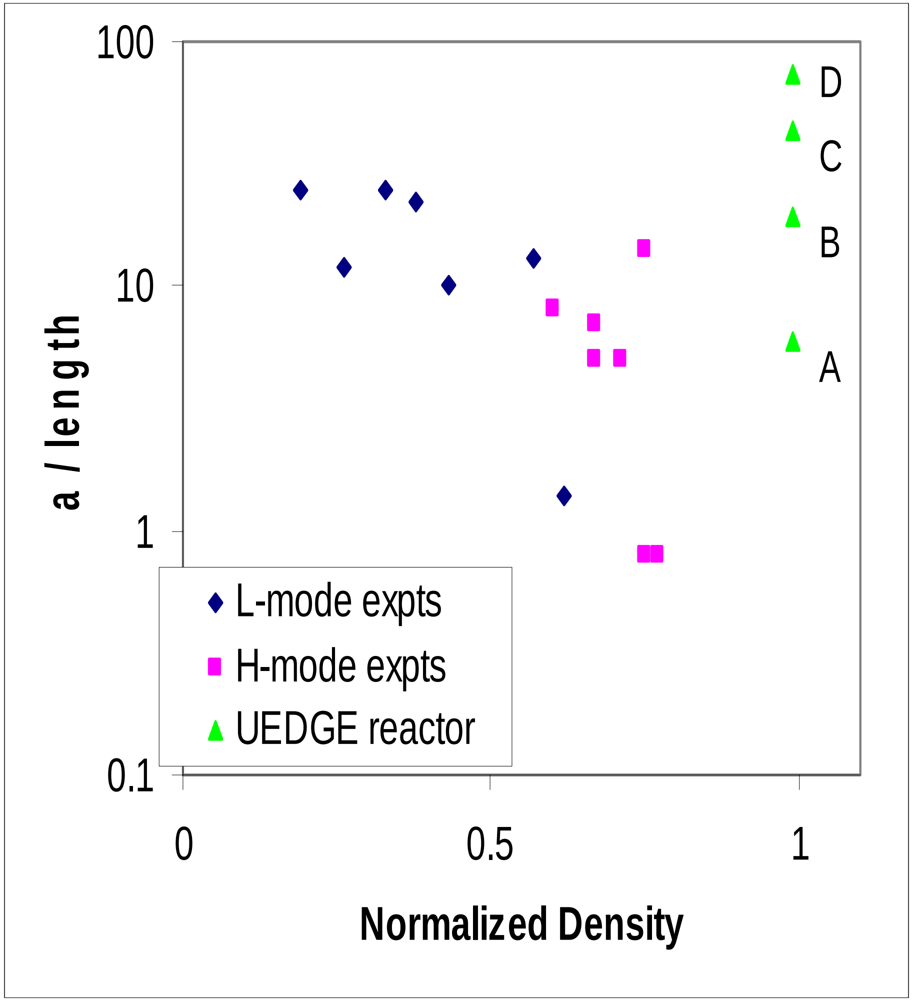
- Find: a strong relationship between the density ratio in SOL and the Greenwald ratio
- For high Greenwald ratio (like reactors), density in the far SOL is high => STRONG WALL INTERACTION
- Case A is most consistent with experiments
- Case D without convection does not match experiments

Density Ratio = $n_{d/a=0.04}/\ n_{sep}$



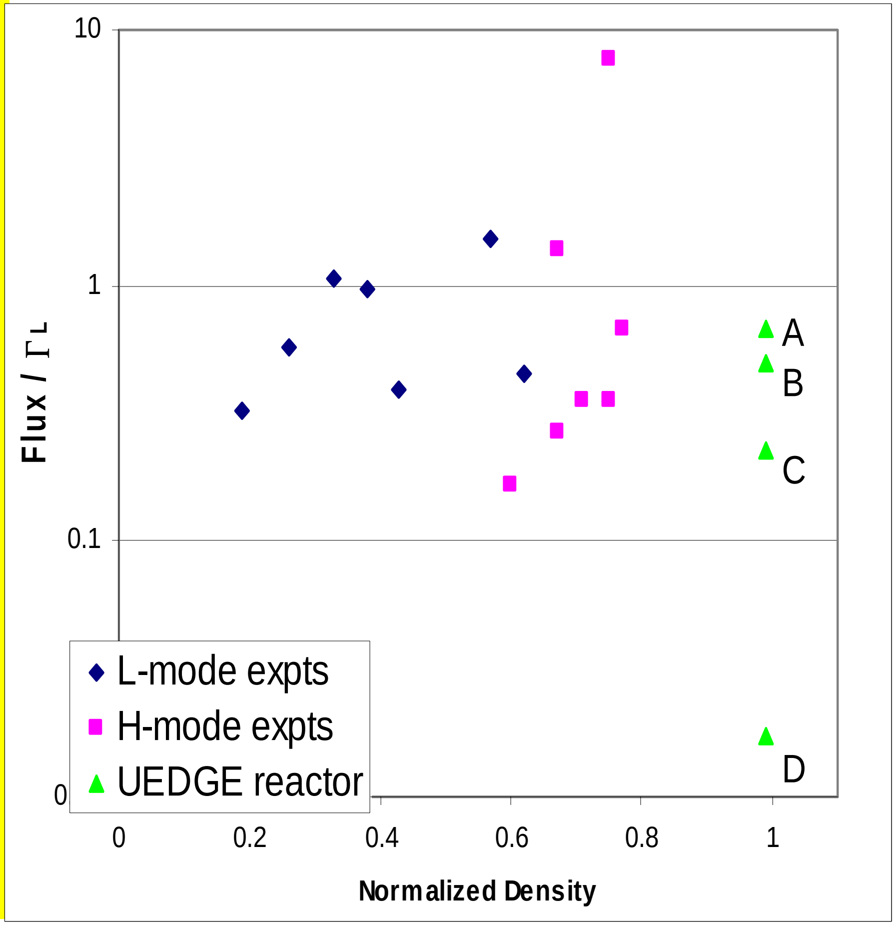
SOL Density Scale Length Comparison

- Find: SOL density decay is slow in experiments, and tends to be flatter at higher density
- Case A most consistent
- Case D without convection: density profile does not match experiments



Wall Flux Comparison

- Experimentally estimated plasma flux to the wall has a large scatter
- Flux trends are described by the expression of Labombard: $\Gamma_L = 10^{21}(n_e/10^{20})^2$
- Case A most similar to data
- Case D without convection: under-estimates flux by nearly two orders of magnitude



Kinetic Neutral Code NUT evaluates the hot CX neutral flux to the wall

- **Wall erosion (for W) is dominated by hot CX neutral flux**
- **The fluid treatment in UEDGE cannot evaluate this**
- **Thus: the kinetic neutral code NUT is used**
  - **NUT: benchmarked against experimental data on TEXT & C-MOD**
- **The plasma profiles and neutral source found by UEDGE are input into NUT**
- **NUT computed the energy distribution of CX neutrals back the the wall**
- **The sputtering coefficient is integrated over the CX neutral distribution from NUT to obtain the wall sputtering**

With Realistic Convection: Strong First Wall Erosion for W

- Most sputtering-resistant material: Tungsten
- Without convection: **0.17 mm/yr**
- With convection: **0.61 mm/yr**
  - Initial rough estimate: small prompt re-deposition (ionization outside sheath, sputtered gyro radius)

Consequences of Tungsten Erosion

- Large dust generation
  - ITER: ~10% of sputtered material forms micron dust
  - With convection: ~ 340 kg/yr dust after 2 years
  - **LOVA dosage marginally <u>exceeds no evacuation limit</u> (even with 99% filter, -adapting analysis of Merril et. al.)**
- High Z Plasma Impurities preclude ignition
  - C-Mod has high-Z wall: H-mode screening factors 1-10%
  - ASDEX ~ 1%   UEDGE ~ 10%
  - This range of screening can have unacceptable consequences:
  - ***<u>H-mode ignition precluded due to radiative losses for ~ 0.5 1.0 % screening factor</u>***

Results for Liquids

- Flibe, LiSn, Sn considered
  - Obviously dust, structural erosion are not issues
- For low Z PFCs (Flibe, LiSn):
  - Plasma: much more tolerant of Low Z impurity
    - Acceptable screening factor ~ 5 %
    - Recall experimental values are ~ 1 - 10 %
  - Sn walls
    - High Z: acceptable concentration slightly higher than W, but sputtering also slightly higher
    - Required screening factor ~ same as W: very worrisome

Implications

- Better physics understanding of SOL transport required: could be show-stopper
  - Plasma-wall interaction: structural erosion, dust
  - Impurity transport and core plasma contamination

- Alternative design concepts required
  - Low-Z liquid walls
    - Low Z liquids => acceptable plasma impurity level
    - Continually replenish wall => no structural erosion
    - Even a thin wetted surface may suffice
  - Field line extraction divertor
    - Low density SOL operation to minimize SOL convection

Beyond FED paper

- **Erosion near edges of protrusions and cavities**
  - **Near corners, projections:** ***blobs will dump plasma much more strongly***
  - **Recycled neutral source many times higher =>** ***Local erosion rates several times higher than for flat wall***
    - **Wall next to ICRF antennas, and antenna itself**
    - **Wall near blanket test modules which are inset by ~cms**
  - **Several mm/year W erosion could be structurally unacceptable in reactor**
- **Assuming ITER edge is the same as ARIES RS calculation**
  - **10,000 shots, 400 sec => ~ 3 mm Be erosion for** ***<u>flat wall</u>***
  - **Several times higher (?) near protrusions and cavities**
  - **ITER Be PFC is 10 mm thick**
- **Possible reactor relevant design solutions (?)**
  - **Low-Z liquid wetted wall near edges?**
  - **Extraction divertor to run in SOL regime with low blob transport?**

Another ITER Issue: Main Chamber Erosion from ELMS

- **Experiments: ELMs cause a "super blob" in the SOL (?)**
  - **Particles expelled in ELMS go to first wall, not divertor**
  - **This is recognized as a possible problem for ITER**
- **Estimate time averaged flux:**
  - **~ 3% particles lost per ELM (similar to energy)**
  - **~ 1 ELM / second**
  - **Implied average flux ~ 10^{18}/m^{2}sec**
- **Estimated flux from steady state blobs ~ 10^{21}/m^{2}sec**
- **Thus: continuous small blobs (considered above) can give much higher average erosion**
- **The seriousness of the continuous blob erosion problem appears to be under-appreciated**

Future Direction: 2 ½ D Simulations of Blobs Coupled to Neutral Calculation

- **3 D simulations are desirable but very expensive (BOUT)**
- **Blobs can be described fairly well with 2 D equations**
  - **Average *along field lines:* Krasheninnikov, D'Ippolito, etc.**
    - **Different "2D" description than implemented in UEDGE**
    - **D'Ippolito found agreement with NSTX blobs with 2D model**
- **Thus: couple 2-D turbulence code (much faster) to NUT**
  - **With NUT, neutral source terms determine SOL profiles**
  - **SOL profiles probably help determine turbulence/blob strength**
  - **Hot CX neutrals determine sputtering**
- **Model parallel conduction/convection from mid-plane to divertor region semi –analytically: the "1/2 D"**
- **2 ½ D simulations MUCH less expense than 3 D => can directly simulate to steady state of the average fluxes**

Future Direction: 2 ½ D Simulations of Blobs Coupled to Neutral Calculation (Continued)

- **This provides a self – consistent physics based model *<u>without empirical fitting parameters</u>***
- **It is fast enough to be used to regularly**
  - **E.g to benchmark with experiments**
  - **To perform parameter scans and trends, give insight**
  - ***<u>Applied to ITER and reactors to estimate erosion</u>***
- **Could also be used to examine dynamics of a large initialized blob**
  - **simulating one produced by an ELM (?)-present ITER issue**
- **May be fast enough to be coupled to an edge sheath model to compute impurity redeposition (? – next slide)**
- **Different approach than UEDGE/BOUT- comparisons obviously would be very important**

Re-deposition of Sputtered Impurities Can be Strongly Modified by Blobs

- **Blobs in the far SOL imply**
  - **Plasma density near/at wall has large variations**
  - **Regions of high density : convecting rapidly toward the wall**
  - **Regions of low density : convecting rapidly *toward the main plasma***
- **The spatial scale of the density variations >> distance for a sputtered atom to be ionized**
- **Thus, consider the fate of impurity sputtered by a hot CX D neutral**
  - **Sputtered wall atoms in regions of low plasma density ionize in the low density plasma**
  - **The plasma impurity is now rapidly convected back to the plasma**
  - **Also, sheath in regions of low density plasma: less prompt redeposition**
- **Thus: *impurity re-deposition could be much smaller than in present models***
- **Bulk plasma contamination could be higher (recall W may preclude ignition)**
- **We would like to couple 2 ½ D simulations above with a rough sheath model (as time and funds permit)**

ICC Grant Awarded to Design Field Line Extraction Divertor

- **Field line extraction divertor: extract separatrix field lines outside the TF coils with novel magnet designs (VERY different coils from bundle divertor)**
- **Previous work (APEX, 2002 APS invited talk) demonstrates this is possible with very low field ripple at the plasma (<< 1%)**
- **Have Received ICC grant to use magnet design tools developed for NCSX Compact Stellarator**
  - **Highly sophisticated algorithms optimize coils for 3-D magnetic fields**
  - **Code produces much simpler, more practical magnet designs for 3 –d problems**
  - **Optimizations can include arbitrary engineering and physics properties (plasma ripple, coil stress, clearance, complexity, heating, etc.)**
- **Thus, a radically different divertor solution may be practical**
  - **Interest from CDX-U, Pegasus and NSTX to develop retro-fit coils**
  - **Large flux expansion outside TF coils could enable low recycling divertor (without Li)- high edge T, low edge n**
    - **Regimes of low blob transport, high core confinement**
    - **Edge conditions more compatible with AT transport barrier modes (DIII-D)**

Conclusions

- **Estimated main chamber erosion is strongly increased by convection**
  - **Plasma impurities for W wall may preclude ignition**
  - **Structural erosion near corners/edges could be unacceptable**
  - **Large dust generation may be problematic (regulatory/social acceptance)**
  - **Issue for future: present models for impurity contaminations and helium exhaust may need to be substantially modified (more pessimistic ??)**
- **Need better models of SOL turbulence & simulations**
  - **More physics based models of SOL blobs & SOL impurities**
- **Unconventional alternatives may be required fusion's feasibility**
  - **Low Z liquid walls (even just a thin wetted surface for erosion?)**
  - **Field line extraction divertor to enable reactor operation in regimes with high SOL T, low SOL n**